Science Challenges for RGB Lighting – Green Efficiency

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glō™

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RGB+ lighting

… is the path to 250 lm/W warm white

which means …

Cree CR Series

SSL can broadly challenge tube fluorescents in commercial lighting and lower the cost of incandescent replacements (less heat to dissipate)

with …

additional functionality of color tunability

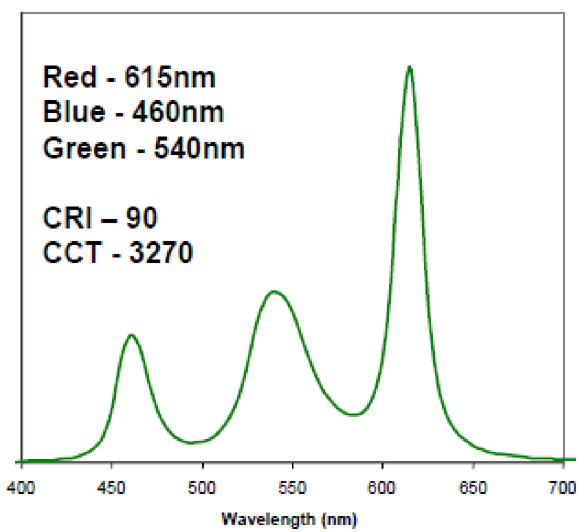
Philips Hue

Efficiency of RGB+

TABLE 3.1 ESTIMATED EFFICACIES AS A FUNCTION OF CCT AND CRI FOR A CM- LED

DoE SSL MYPP 2013

CCT (K)	Maximum LER (lm/W)			Efficacy for 67% Conversion (lm/W)		
	CRI 70	CRI 85	CRI 90	CRI 70	CRI 85	CRI 90
5000	380	365	356	255	245	239
3800	407	389	379	273	261	254
2700	428	407	394	287	273	264



- When RGB all exceed 40% wall plug efficiency, then 150 lm/W color-tunable white is achievable
- Red and blue are already at this performance
- Improving green is the key

Science Challenge : Green Efficiency

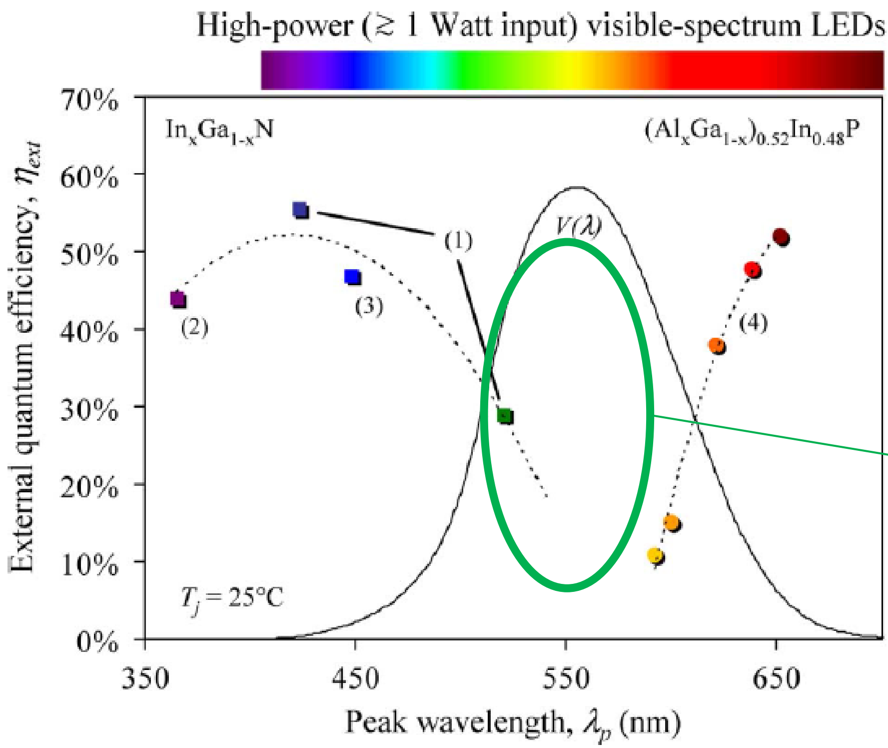


Fig. 2. State-of-art external quantum efficiencies for high-power visible-spectrum LEDs ($T_j = 25$ °C): (1) InGaN TFFC LEDs, 350 mA (this paper); (2) InGaN VTF LED, 1000 mA [42]; (3) InGaN CC LEDs employing patterned substrates [35]; and (4) Production performance, AlGaInP TIP LEDs [9], Philips Lumileds Lighting Co., 350 mA. $V(\lambda)$ is the luminous eye response curve from CIE. Dashed lines are guides to the eye.

Krames, et al., IEEE J. Display Tech., June 2007

Green gap

~20% WPE

Start by doubling…

Semiconductors emitting in the green

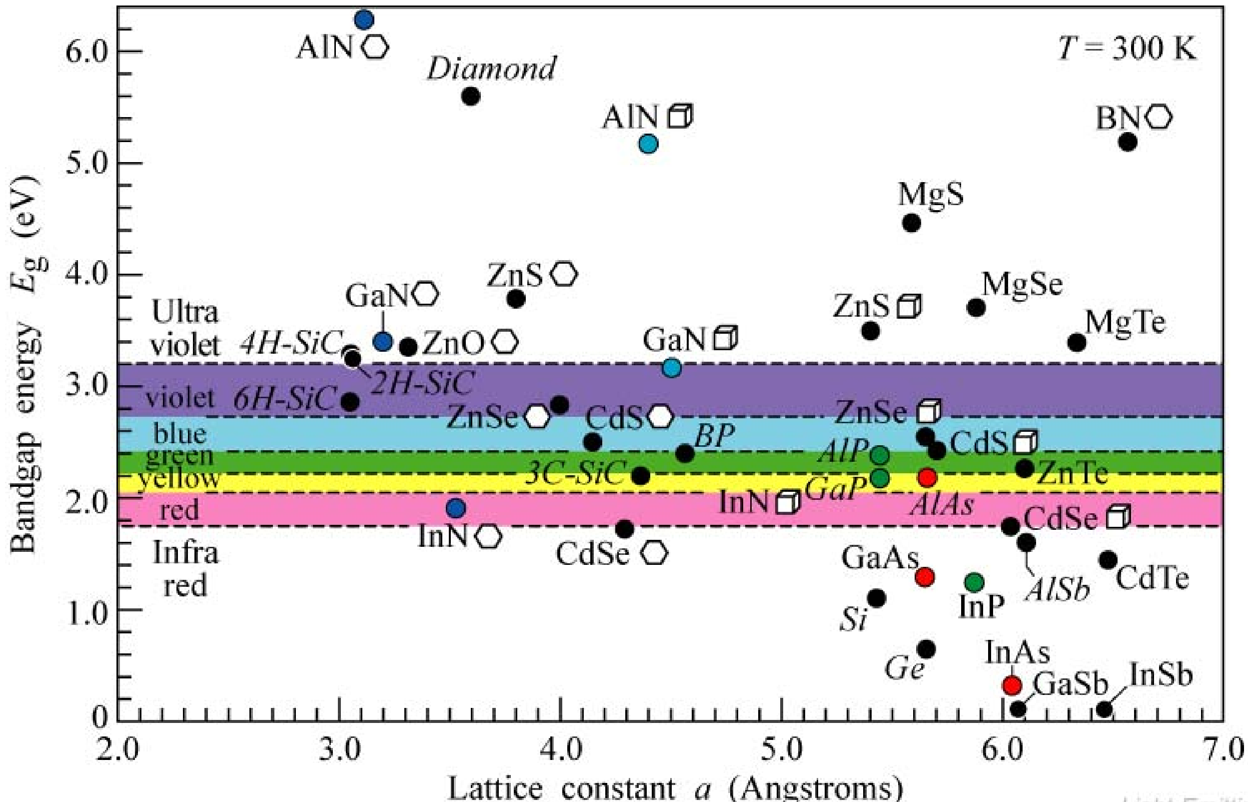
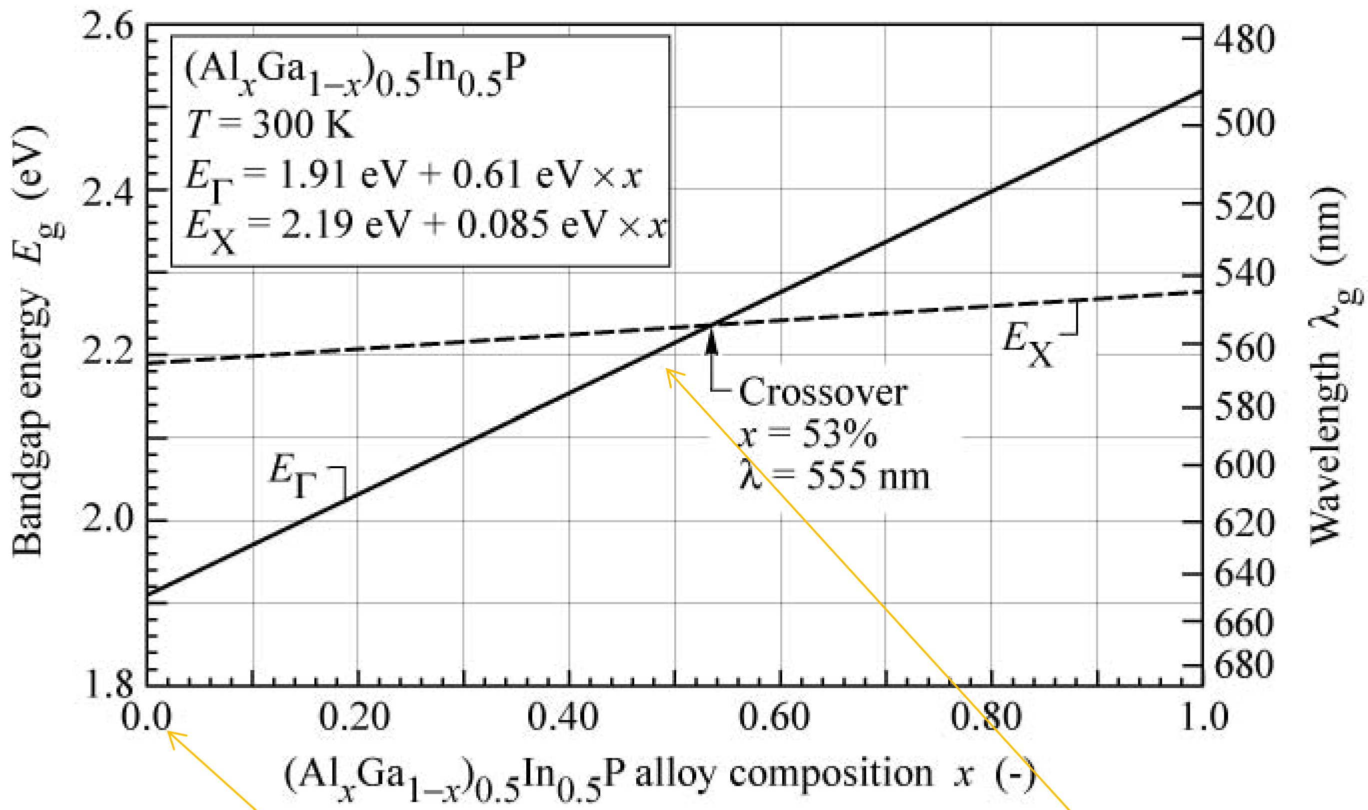


Fig. 21.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.

Today's contenders: AlInGaP, w-InGaN – dominant LED materials

Can others play? ZnCdSe? Cubic InGaN? long list…

AlInGaP – a fundamental energy band problem with green

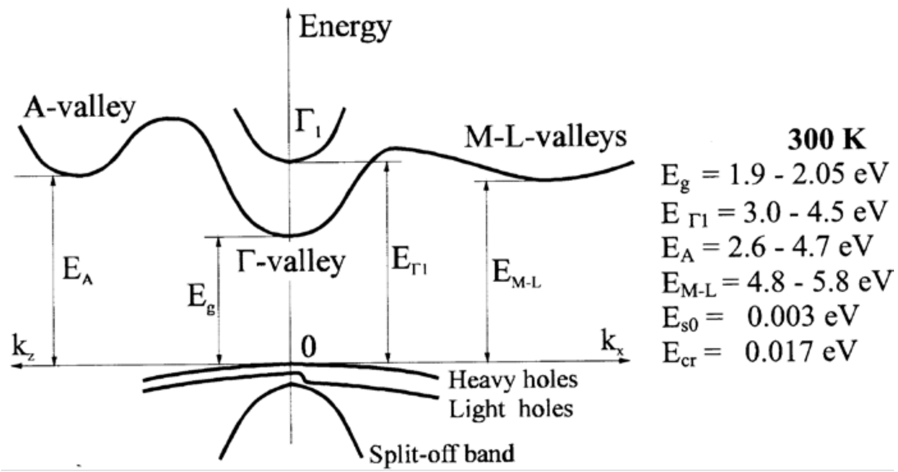


Only a few% efficiency here

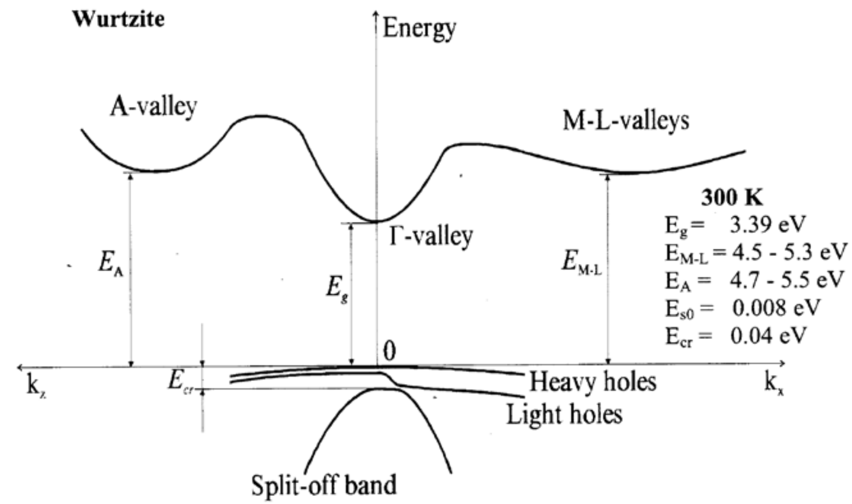
Almost 100% efficiency can be achieved here

InGaN bandstructure – looks good

InN



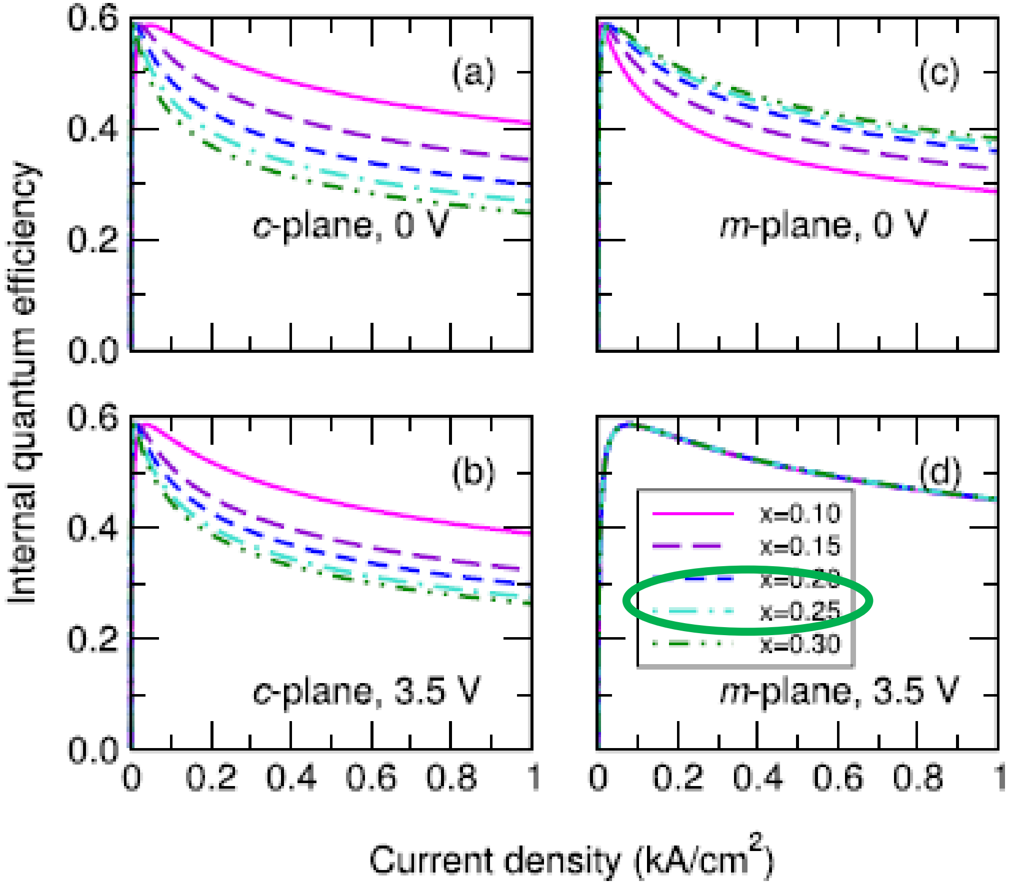
GaN



Suzuki, M, T. Uenoyama, A. Yanase, First-principles calculations of effective-mass parameters of AlN and GaN, Phys. Rev. B 52, 11 (1995), 8132-8139.

Indirect band minima located far from Γ point

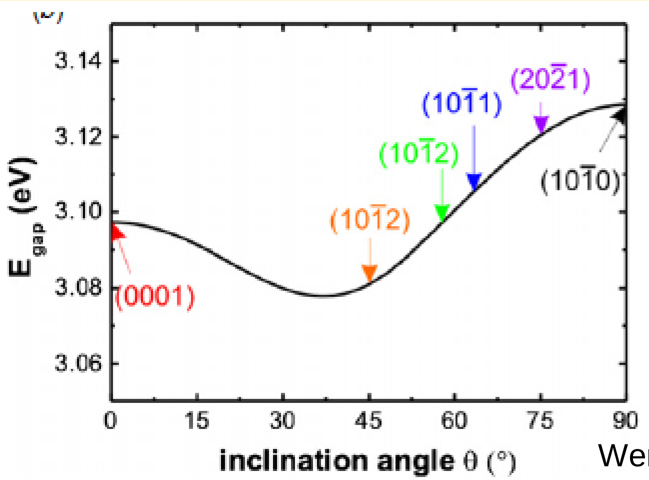
Auger recombination contributes



- Green c-plane QWs exhibit more Auger recombination than Blue QWs because QCSE reduces rate coefficients

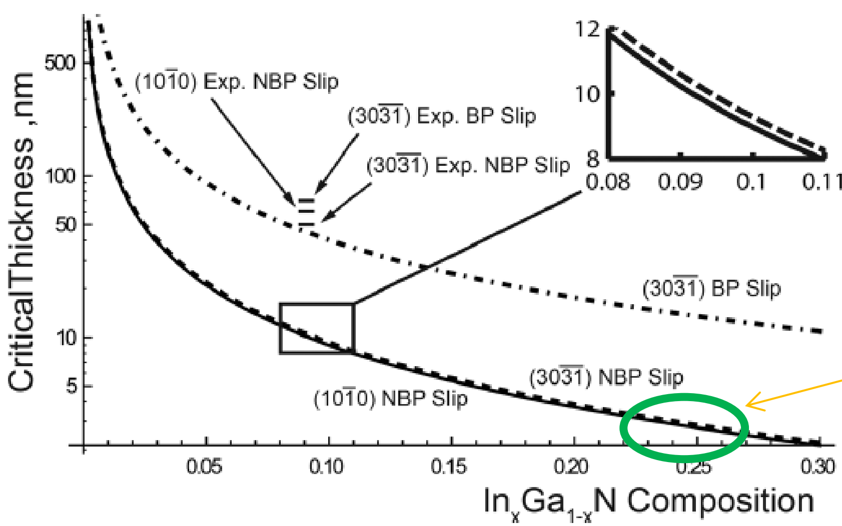
Kioupakis, et al., Appl. Phys. Lett. 101, 231107 (2012)

Non-polar planar could help, but growth conditions and strain hurt…



- More indium is needed when growing on non-polar plane → need to lower growth temperature → more non-radiative recombination centers

Wernicke, et al., Semicond. Sci. Technol. **27** (2012) 024014

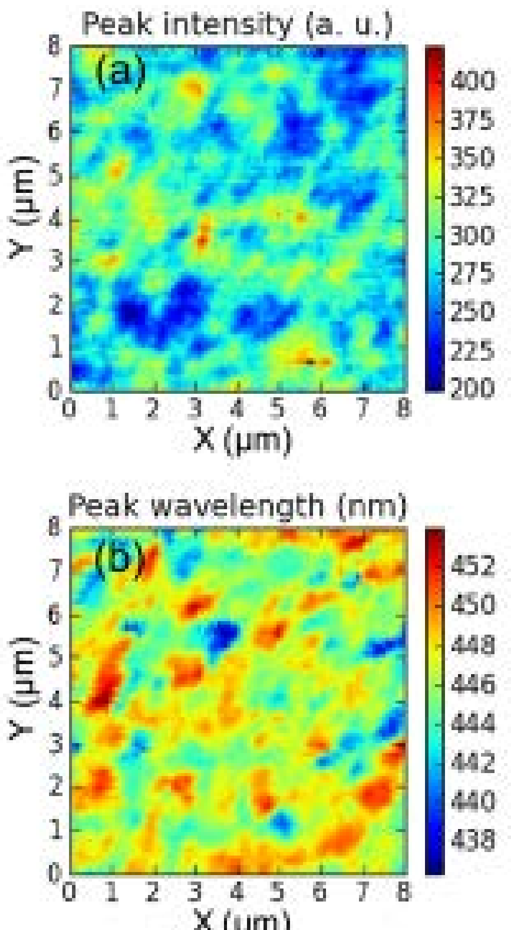


Too thin! Can't make a QW

Hsu, et al., Appl. Phys. Lett. 100, 171917 (2012)

InGaN alloy tries to relieve its stress by becoming nonuniform, even in the blue compositional range

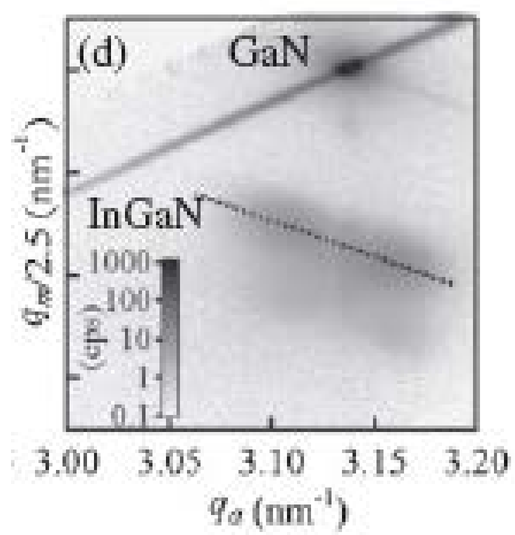
Near-field PL



Marcinkevic˘ius, et al., Appl. Phys. Lett. 102, 101102 (2013)

- Effect is stronger in the green
- Limiting factor for green laser performance
- Optimization of growth conditions by several groups trying to address this

Tilt domains observed in XRD



Shojiki, et al., Jpn. J. Appl. Phys. 51 (2012) 04DH01

Growth on “foreign” substrates which relieve strain

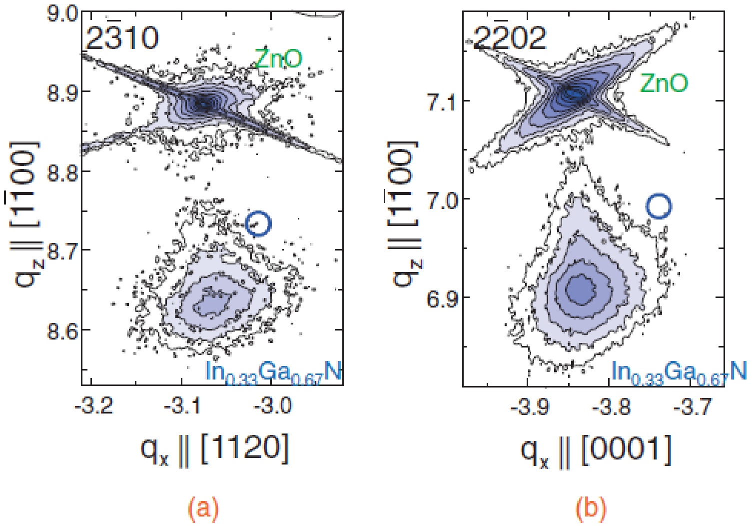
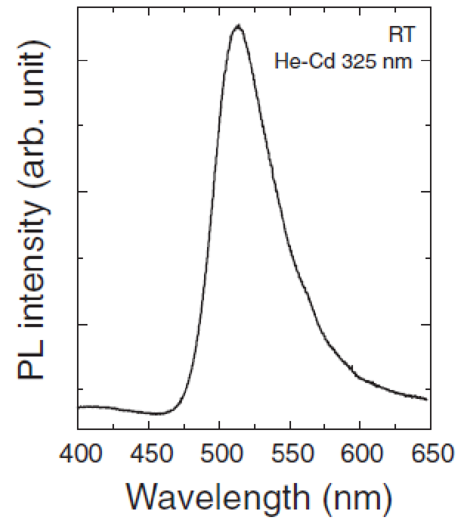


Fig. 3. Reciprocal space maps for (a) 2$\bar{3}$10 and (b) 2$\bar{2}$02 diffractions for *m*-plane $In_{0.33}Ga_{0.67}N$ on ZnO. The reciprocal points for bulk $In_{0.33}$-$Ga_{0.67}N$ are also shown as the open circles in the maps.

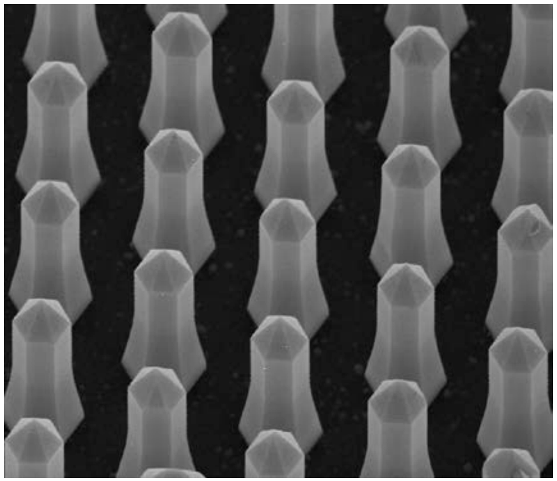


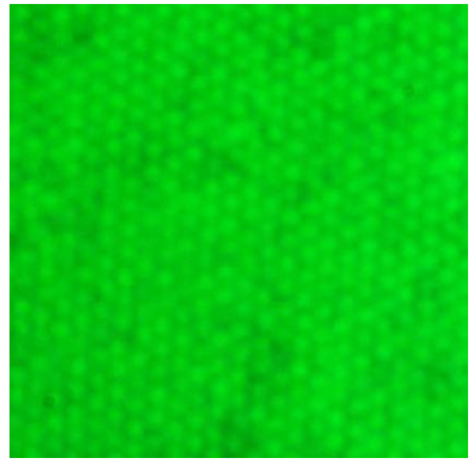
Shimomoto, et al., Appl. Phys. Express 3 (2010) 061001

- InGaN lattice matched to ZnO

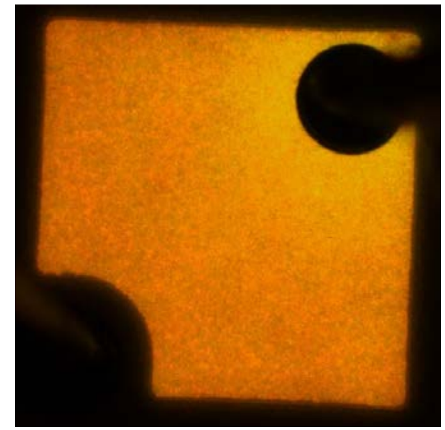
- Other approaches:
  - strain-relaxed InGaN-on-sapphire templates from Soitec (epitaxial lift-off)
  - other ways?
- Drawbacks: substrate cost has to be competitive with sapphire

Nanometer texturing/nanowires to address these issues





- Glo nanowire LEDs



- Provide textured template for InGaN to "master" the strain
- Small sizes → edges, corners can accommodate stress, enabling a defect-free QW
- Can be cost effective, uses many existing materials & technologies

Better green is a tough problem….

worth solving …

for SSL and many other applications (displays, medical instrumentation)

High risk & high reward ---- Core Technology